

Full TPC Simulation

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on behalf of BNL group

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Introduction

Brett's introduction to wire-cell toolkit (first LEE ana meeting) <https://indico.bnl.gov/conferenceDisplay.py?confId=3180>

This talk:

- ✓ **Functional 5 D's + OutputFrame** in wire-cell toolkit (WCT)
<https://github.com/WireCell/>
- ✓ **Fundamental Physics & Math** in WCT sim
- ✓ Not include technical/algorithmic details in implementation and speed & memory control

What components we have in the full TPC simulation?

Overview of full TPC simulation

$$Wave = Depo \otimes \text{Drift} \otimes \text{Duct} \otimes \text{Digit} + \text{Noise}$$

Output:
✓ 2D Histograms
✓ Celltree-like

✓ LarSoft G4 simulation (deposited energy, time, position, ionizing electron, etc.)
✓ Manual input (obey the input file rule)
✓ TrackDepos (WCT tool to generate simple track depo)

2 MHz sampling,
max 2000 mV,
12-bit ADC

(Dissonance)
Data-driven

Random Walk

$$F(\omega) \propto \sum q_i \cdot e^{-i\omega t_i}$$

✓ Field response (2D garfield calculation)
✓ Pre-amplifier electronic response (gain, shaping time)
✓ Additional two independent RC filter response (RC constant)

Key convolution:

$$[Gaus(t) \cdot Gaus(x)] \otimes field(x, t) \otimes Preamp(t) \otimes RC(t) \otimes RC(t)$$

✓ Ionization (W-value, fano factor)
✓ Recombination (Birks & Modified box models)
✓ Ionizing electron attachment (electron lifetime in LAr)
✓ Gaussian diffusion (longitudinal / transverse)
✓ Fluctuation (each step)

Field response (1)

- Electric field response

Shockley–Ramo theorem

$$i = q \cdot \vec{E}_w \cdot \vec{v}_q$$
$$\int i dt = q \cdot (V_w^{end} - V_w^{start})$$

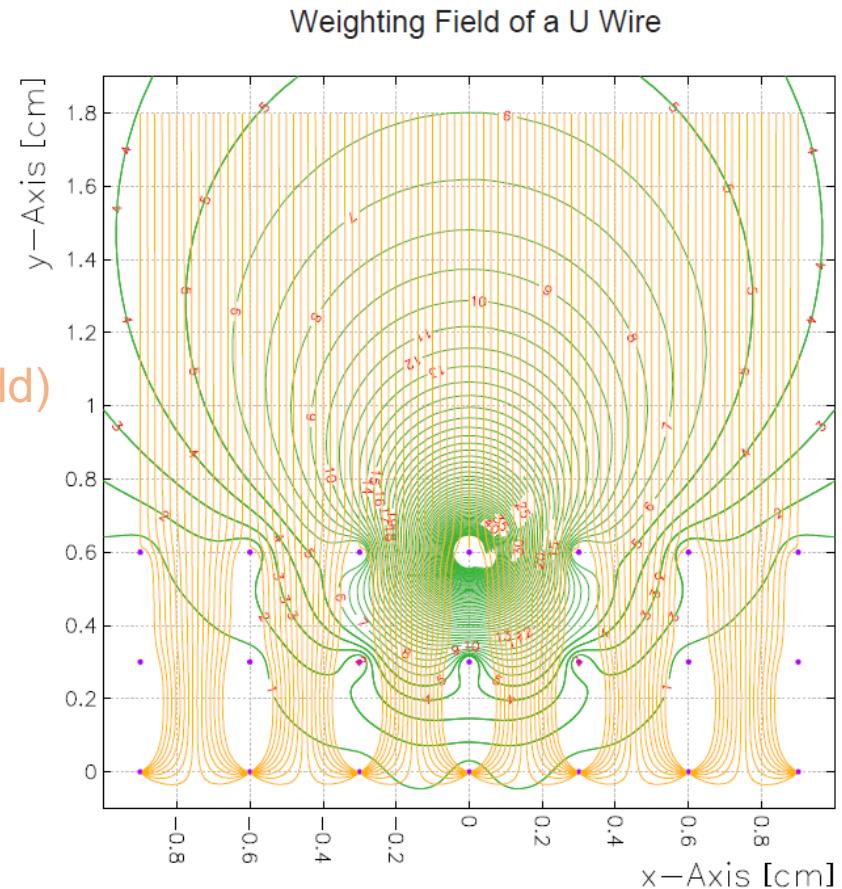
E_w/V_w : weighting electric field/potential, placing the target wire to the unity potential, and the rest to zero

EM reciprocity

Electron
track (E field)

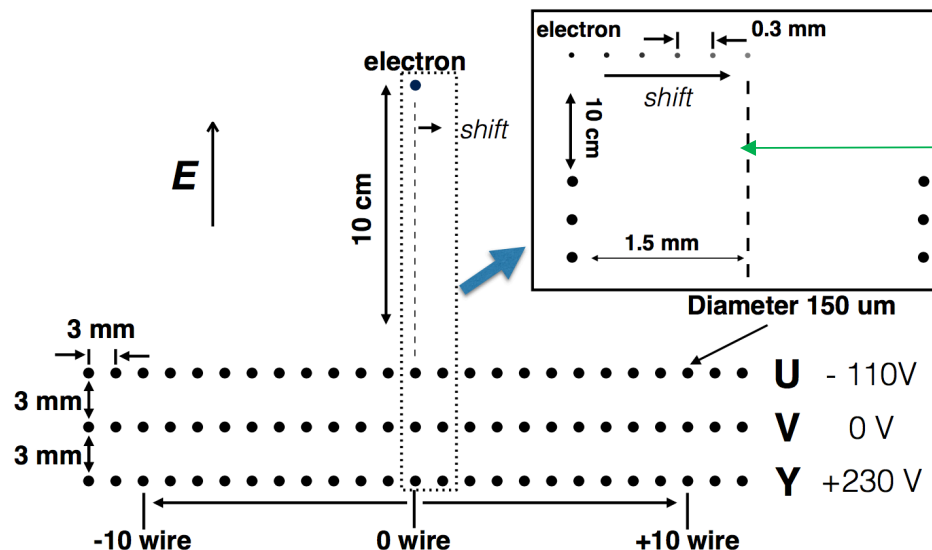
+

Weighting
potential



Field response (2)

- Input 2D Garfield calculation (contribution from adjacent wire regions)
 - Each wire region ± 1.5 mm: 6 sub-positions (5 sub-pitches/0.3 mm), the other half is symmetrical (special: 1.5 mm wire pitch boundary for collection planes).
 - Take into account 21 wires (0 ± 10) X 6 sub-positions = 126 field responses for each plane

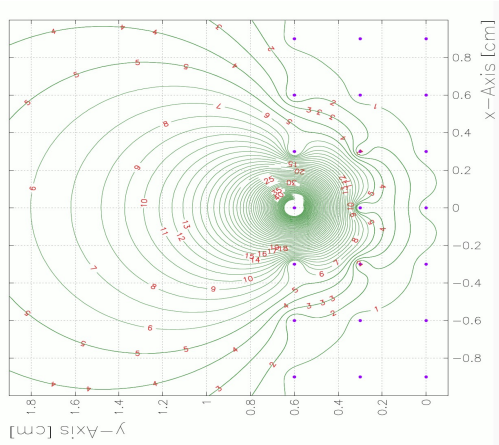


- For an electron,
- ✓ exact 1.5 mm: bypass collection plane (negligible phase space)
 - ✓ $1.5_{+/-}$ mm: collected by target/adjacent wires (quite different pathology)

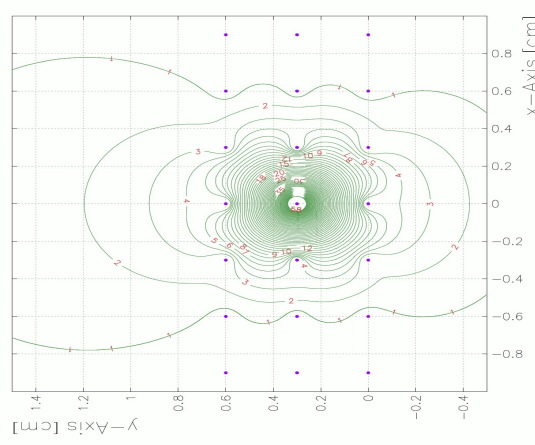
Field response (3)

Weighting potential

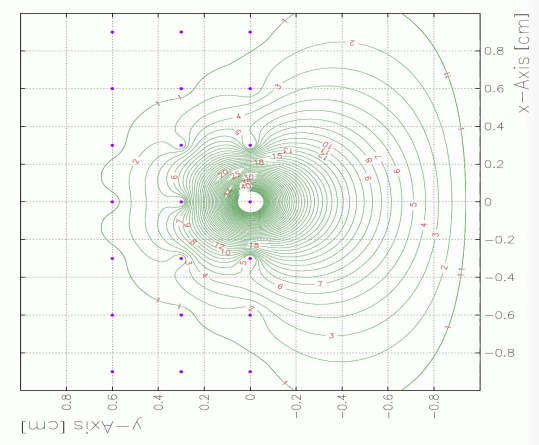
U plane



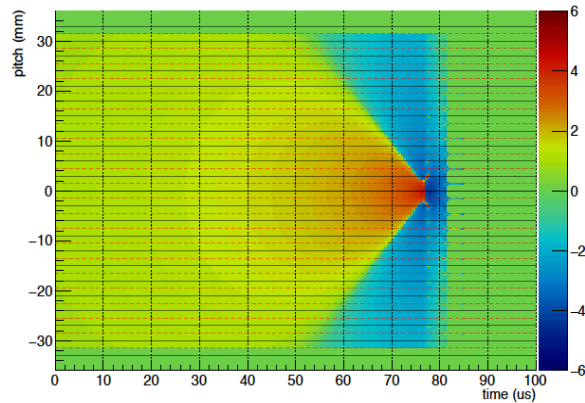
V plane



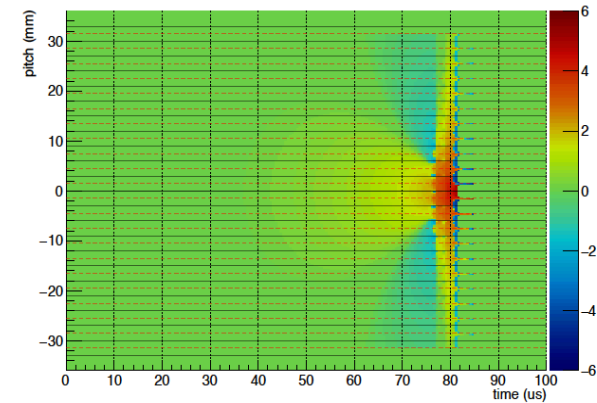
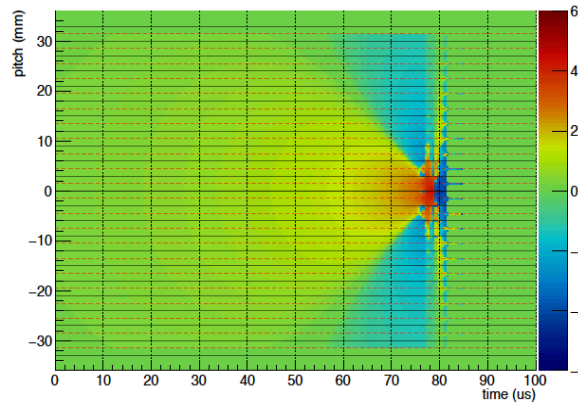
Y plane



Field response (Plot in log scale, arbitrary unit)



6/18/17

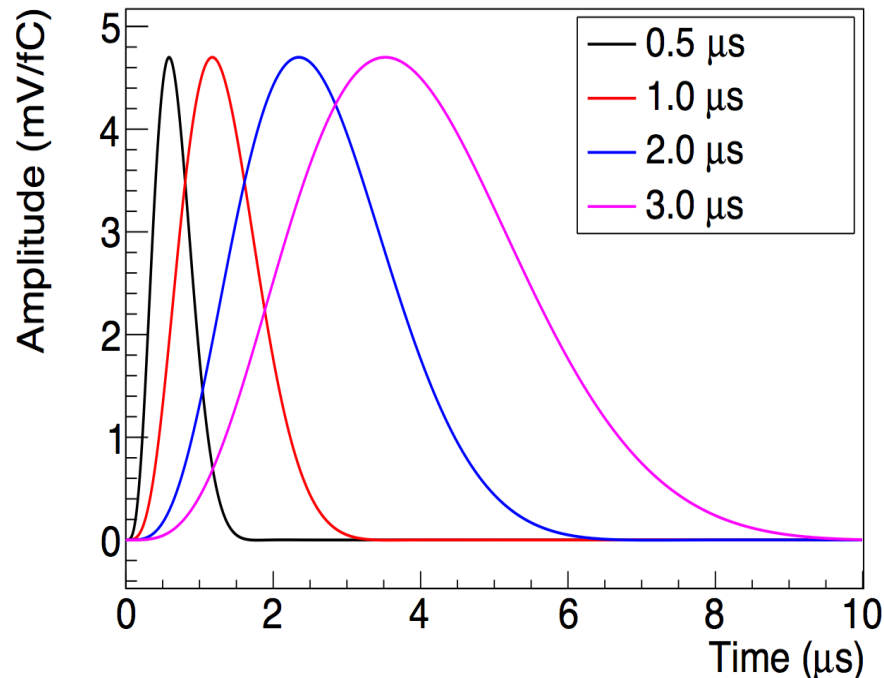


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Electronics (impulse) response

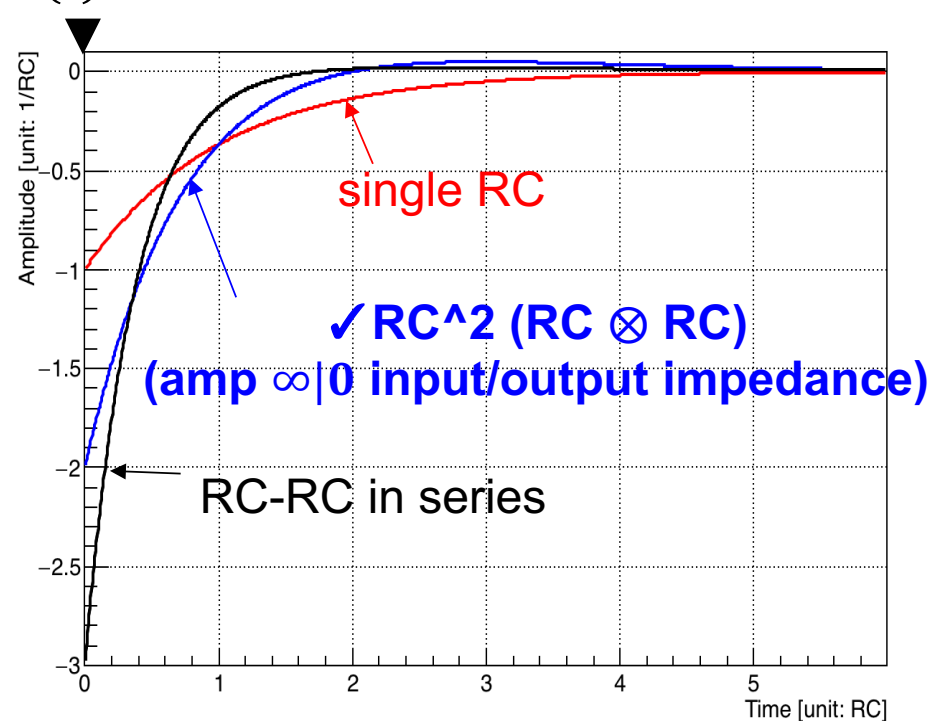
- Pre-amp
(analytical)

Electronics Response Function in Time Domain



- RC filter
(analytical)

$\delta(t)$ here

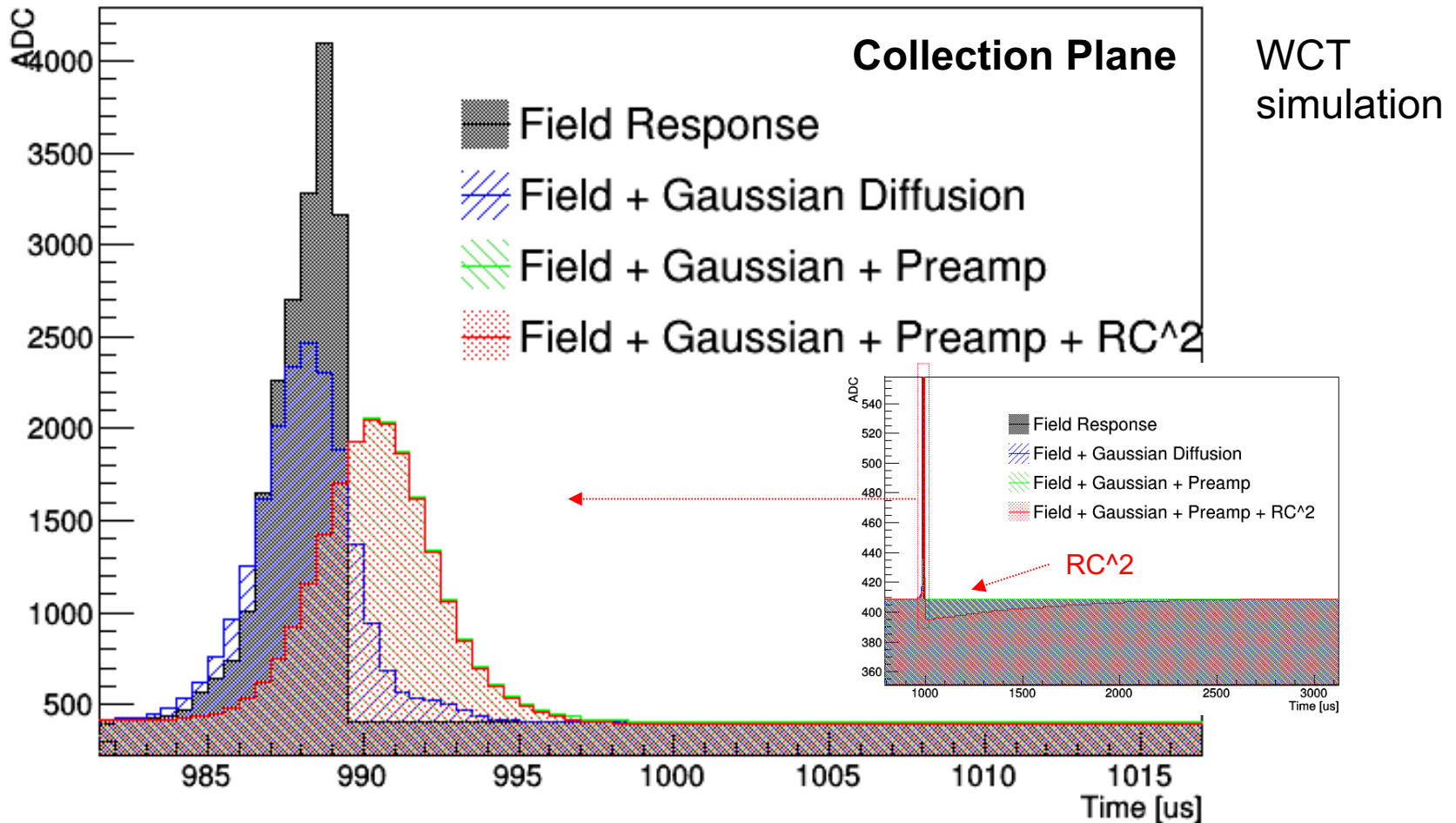


These time-domain responses are obtained by inverse Laplace transform on s-domain responses

Multiple responses

- Multiple electronic responses
 - Mis-configure channels
 - Dead channels
- Multiple field responses [ongoing]
 - Shorted wires

Point charge depo waveforms



Interpolation of field response

- Real physics has continuous & changing field response
- Interpolation is necessary, 10 sub-pitches are not adequate
- From two nearest field responses

$$\int \underset{\substack{\text{Charge spectrum} \\ \text{after diffusion}}}{q(x, t)} \otimes \left(\underset{\substack{\text{Field response}}}{f_1(t)} \cdot u(x) + \underset{\substack{\text{Field response}}}{f_2(t)} \cdot (1 - u(x)) \right) dx$$

e.g. linear
 $u(x) = \frac{x - x_2}{x_1 - x_2}$

Integral: on x
Convolution: on t

$q(x, t) = q(t) \cdot Gaus(x)$

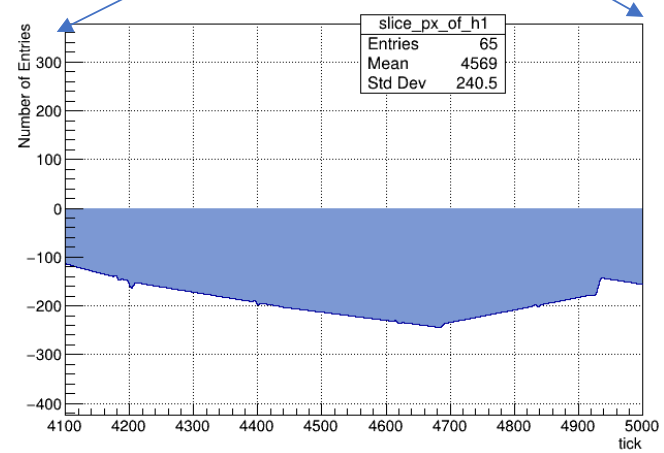
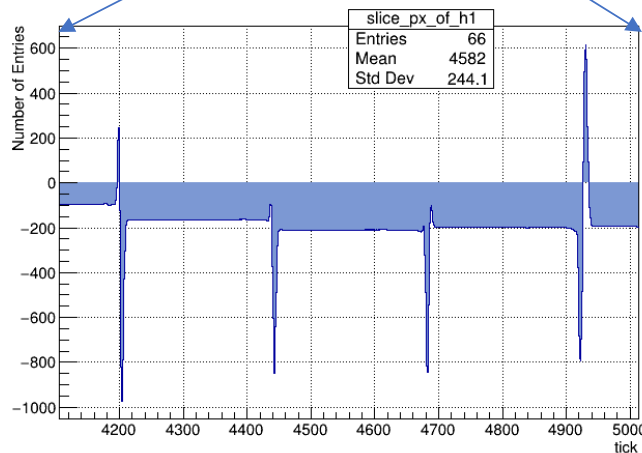
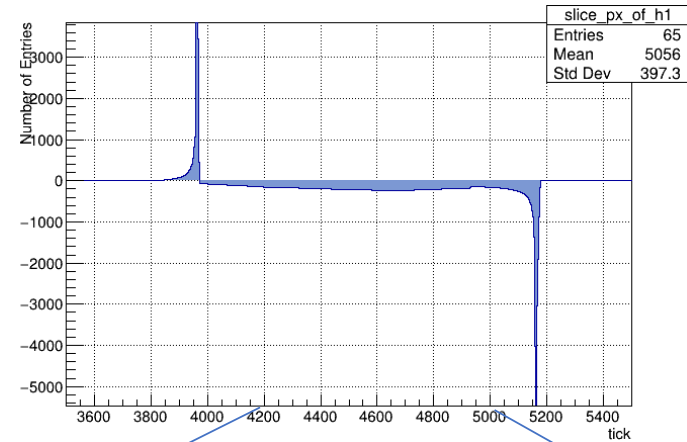
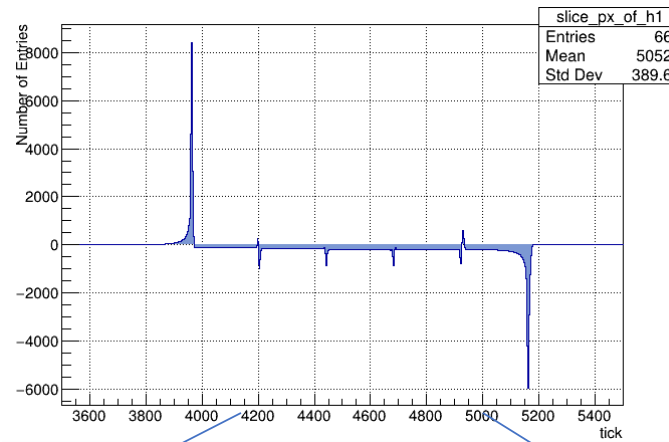
$$\left\{ \int Gaus(x) \cdot u(x) dx \right\} \times q(t) \otimes f_1(t) + \left\{ \int Gaus(x) \cdot (1 - u(x)) dx \right\} \times q(t) \otimes f_2(t)$$

Interpolation of field response → re-distribute (weighting) charge depo to the two nearest field response positions against relative distance in x)

Track ~ 60 cm length in X, 3 mm width in Z

Every 0.003 mm a charge depo along the track without diffusion

Induction
Plane (V-
plane)

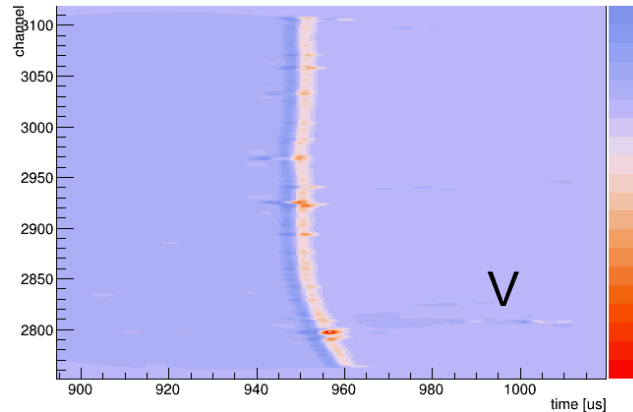
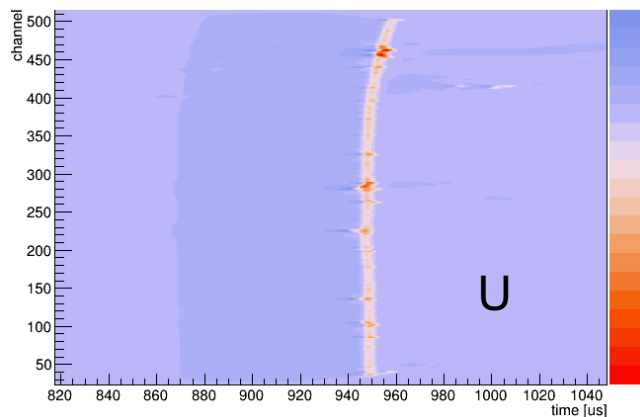


Averaging (weight=0.5)

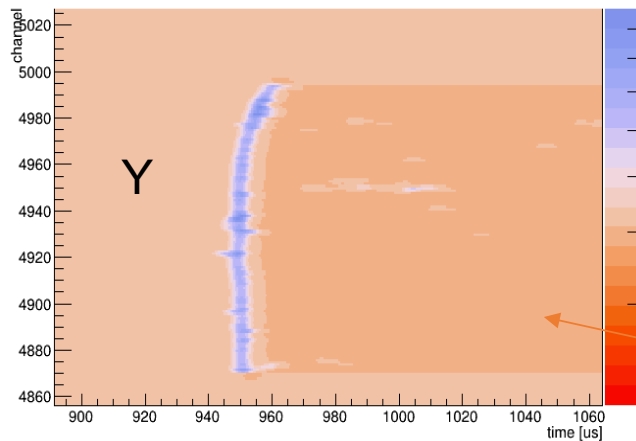
Linear interpolation

A full simulation of LArSoft track

- 5 GeV muon track from LArSoft G4 simulation



Log scale
Baseline: 1843
Range: 1656 - 1910



Log scale
Baseline: 410
Range: 200 - 974

Tiny negative RC² response tail

Front-end ASIC inherent noise

From Milind Diwan

noise type	also called	normalization	Time Domain pulse	s domain	
Thermal 1	series white	$\sqrt{2k_B T_{temp} R_S} \times C_{det}$	$\times G \cdot \delta(t - t_j)$	$\times G \cdot e^{-st_j}$	Thermal fluctuation in the input transistor
Thermal 2	parallel white	$\sqrt{2k_B T_{temp} / R_F}$	$\times G \cdot u(t - t_j)$	$\times \frac{G}{S} \cdot e^{-st_j}$	Transistor bias current and resistors providing the bias voltage
Shot noise	parallel white	$\sqrt{qI_{leakage}}$	$\times G \cdot u(t - t_j)$	$\times \frac{G}{S} \cdot e^{-st_j}$	
Flicker noise (1/f or pink)	series 1/f	$C_{det} \sqrt{2\pi a_F}$	$\times \frac{G}{\sqrt{\pi} \cdot (t - t_j)}$	$\times \frac{G}{\sqrt{s}} e^{-st_j}$	Charge trapping and de-trapping in the input transistor
Man made noise	Various couplings	Usually has discrete frequency spectrum. Ignored here, could be modeled.			

- ❖ t_j is uniformly distributed (origin of the fluctuations)
- ❖ White noise (e^{-st_j}) can be treated as the origin of other sources of noise (with a scale factor related to frequency)

"Noise Characterization and Filtering in the MicroBooNE TPC", MicroBooNE collaboration, submitted to JINST, arXiv:1705.07341

Inherent noise simulation

- See more details at <https://indico.fnal.gov/getFile.py/access?contribId=30&sessionId=12&resId=0&materialId=slides&confId=12345>
- Key points:
 - White noise can be treat as the origin of all the other source of noise (stochastic behavior)
 - In freq-domain, any noise is a high-dimension random walk in complex plane.
 - The amplitude follows Rayleigh distribution
 - The phase follows uniform in 0-2pi
 - Additivity (sum up all sources of noise)

$$f(x; \sigma) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}} \text{ (Rayleigh Distribution)}$$
$$\text{Mean} = \sigma\sqrt{\pi/2}, \text{ Mode} = \sigma, \sigma = 0.5 \cdot N \cdot L^2$$

N: number of steps
L: step length

Data-driven noise simulation

- In freq-domain, given a frequency, the mean amplitude is the only parameter we need for noise simulation.
- Two independent Gaussian distributions for real & imag parts can simulate the Rayleigh amplitude and uniform phase in the complex plane.
- Data: freq-domain spectra of mean amplitude
 - 1 length for collection plane
 - 13 lengths of wires for U, V planes
 - Series white and pink noise has linear item of $C_{wire} \propto L_{wire}$
 - Linear interpolation based on two nearest lengths

Noise simulation

